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Harmonic Modelling of Power Systems HV Cable: A Novel Approach

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ABSTRACT

This research demonstrated an innovated approach of modelling high voltage underground cable for analysis in frequency domain presented. The approximation cable model method was found useful in determining the resonant frequencies in the case of an offshore power generation plant connection to the transmission line through high voltage cable. The generated results indicated that the presence of cables in the power transmission system could contribute to the occurrence of high harmonic resonances at low order harmonic resonant frequencies. In this research numeric results were computed, simulated and subjected into several graphs readings as shown in Figure 2, 7, 8, 9 and 10 respectively.

Keyword: Harmonic, Modelling, Power systems, HV cables, Novel, Novel approach

1. INTRODUCTION

The offshore power generation industry has developed very rapidly in recent years. Therefore, to model onshore and offshore electrical power systems successfully, it is necessary to have accurate impedance models of the underground and subsea cables otherwise, it is impossible to reliably predict system resonances and the effects of any generated harmonics from power electronics converters. As the oil and gas industry expand toward deeper sea, the cable circuits tend to increase in length. At present, cable circuits are being employed which have lengths of the order of 100km. To develop accurate impedance models, a good understanding of the physical phenomena that goes into the design of the cable impedance is necessary. Also, for the power system studies, the steady-state and harmonic generation of cables must be known. Over the years research has been tailored to determine a suitable model for calculating the impedance of overhead cables. This is contrary to underground and subsea cables which have different layers of heavy armour on the outside to give added strength both for laying and protecting against mechanical damage. Because of the heavy armour, the electromagnetic effects between the layers within the subsea cable need to be considered carefully when developing impedance models. Subsea cable arrangements and

structures are diverse with inductive and capacitive element which suggests that each cable type will generate a harmonic resonance characteristic [1, 2].

A novel approach that matches the overhead transmission line is difficult for underground and submarine cables due to their extremely complex construction and layouts. In this paper a single conductor aluminium cable with a concentric lead sheath and with insulation of XLPE is studied in detail.

Cables are principally classified based on

- Their location, i.e. aerial, underground and subsea
- The number of conductors, i.e. single, two and three conductor and so on
- The type of insulation, i.e. oil-impregnated paper, cross linked polyethylene (XLPE) etc.
- Their protective finish, i.e. metallic (lead, aluminium) or non-metallic (braid)

The cross section of an XLPE cable is as shows in Fig. 1, the offshore cable (submarine cable systems) which is made up of a core, insulation, sheath and armour, suitable for energy transportation in upstream and midstream power systems, maybe also suitable for underground single-core coaxial cables (SC cables). However, SC cable with actual conductor, sheath and armour are quite often seen in the offshore power systems [3][4]. In this thesis two high frequency cable models are investigated and their harmonic resonance predictions are compared. The former is an approximate model. The approximate model can give the relative contributions of the various cable materials to the propagation characteristics of the cable. Emphasis is put on the current excitation shorted end and voltage excitation opened end. The latter is a modified Bessel function model which permits perfectly representation of the electrical properties such as resistivity, permeability and permittivity of the earth which form the return path for current flowing in the cable [5] [6][7].

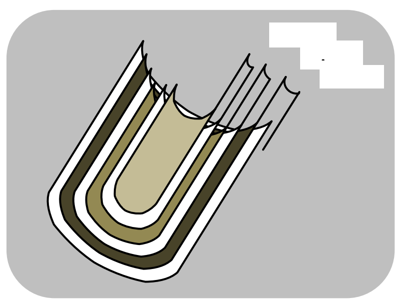


Figure 1. Bisection of the construction of the 23-kV single-core cable with three dielectric, operating frequency is 50Hz.

The rigorous representation of such factors (electrical properties) would lead to very complex equations which may be solved by computational method and could offer more acceptable results. Simplifying assumptions are made:

- The cables are of circularly symmetric type. The longitudinal axes of cables which form the transmission system are mutually parallel and also parallel to the surface of the earth. This implies that the cable has longitudinal homogeneity. Alternatively, the electrical constants do not vary along the longitudinal axes.
- The change in electric field strength along the longitudinal axes of the cables is negligible compared to the change in radial electric field strength. This assumption allows the solution of the field equations in two dimensions only.
- The electric field strength at any point in the earth due to the currents flowing in a cable is not significantly different from the field that would result if the actual current was concentrated in an insulated filament placed at the centre of the cable and volume of the cable were replaced by the soil.
- Displacement currents in the air, conductor and earth could be ignored.

Ground Return Impedance of Underground Cables

The unit-length series impedance of cylindrical conductor with radius r_{ext} buried at depth y in the earth with conductivity σ, permeability μ_o and dielectric constant ε, consists of two terms: conductor internal impedance Z_i and impedance of ground return Z_o [3]. The conductor internal impedance only indicate constant response as represented in Fig. 2a, this reveal the internal impedance of the conductor as a function of the thickness of the conducting layer. At frequencies 50 Hz and 1 kHz, the impedance

remains constant at the whole range of the thickness. While the summation of internal impedance together with impedance of ground return indicate resonance response as shown in Fig. 2b. As observed, we could apparently state that the impedance when loaded with ground return impedance affects very significantly the magnitude of the frequency of the system response. In image theory the electromagnetic field for underground cables results from the conductors and their corresponding images. The earth contribution is much more significant as the actual conductors are buried inside it and their image in the air as shown in Fig. 2. This leads to infinite integrals for the self and mutual earth return impedances which are different from the corresponding overhead lines. They include highly oscillatory functions which are easily computed using Dubanton's formulas [8].

According to (4.56), [Z_o] represent the impedance ground return path of a cable system using complex penetration as shown in Fig. 3.

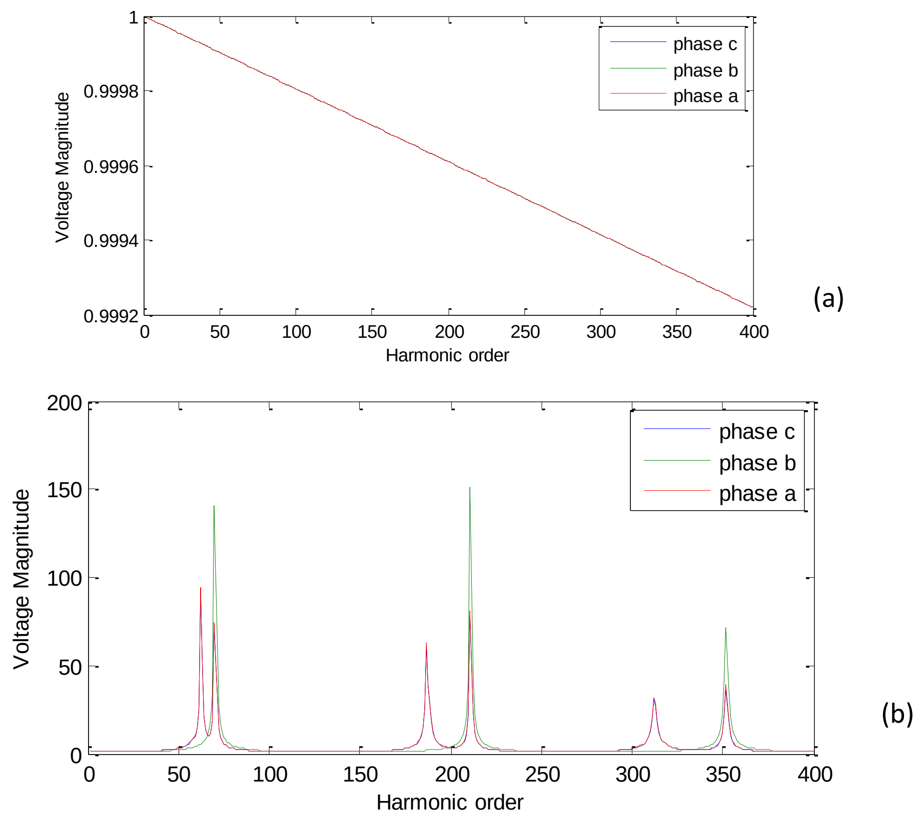


Figure 2. Internal impedance of the cable system (a) without ground returns impedance (b) with ground returns impedance

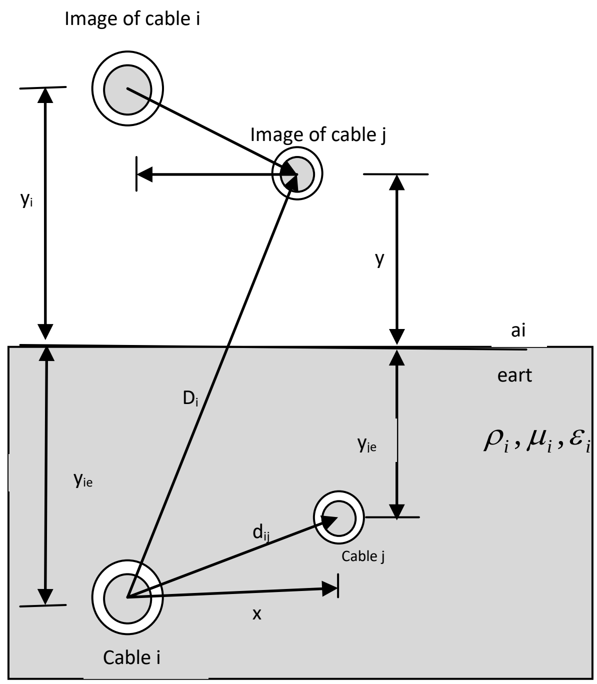


Figure 3. Geometric configurations of two SC underground cables and its images

The elements of the matrix of ground return path impedance Z using Dubanton's equations are given by the self-ground impedance

$$Z_{0ls} = \frac{j1000\omega\mu_0}{2\pi}\ln\left(\frac{1+\rho}{r_{ext}}\right) \quad (1.0)$$

while the mutual ground impedance is given as

$$Z_{0lm} = \frac{j1000\omega\mu_0}{2\pi}\ln\left(\frac{1+\rho}{dij}\right) \quad (1.1)$$

where

$$dij = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (1.2)$$

$$\rho = \frac{1}{\sqrt{j\omega\mu_0\sigma}} \quad (1.3)$$

where

ρ is the complex depth above the earth at which the mirroring surface is located.

μ_0 = 4π x 10^{-7} H/m is the permeability of free space

σ is the conductivity of the conductor in S/m

2. FORMATION OF APPROXIMATION CABLE MODEL

Several approximations with closed-form solutions have been investigated in the issue of overhead transmission line, but nothing promising has been investigated in the issue of underground and submarine cables.

In this approach of complex depth concept, the infinite integral of impedance of the conductor, and sheath taking due account of skin effect each of which is approximated using infinite series. The current inside conductor is concentrated around the surface due to the skin effect. It is assumed that the current density is uniform in the range covered by the skin depth. Under this assumption, the internal impedance can be derived by approximation method.

In the supporting routines cable parameters of harmonic study, the earth return impedances of cables are calculated using Dubanton's formula for a single case of two underground conductors, which is evaluated by infinite series. The model is valid for homogenous infinite earth, neglecting the displacement current [9][10].[11][12][13].

Underground and submarine cables are usually divided into single or multiple core types. For high power, three-phase AC transmission cable systems could be designed as either a single-core cable or three single-core cables or as a single three-core cable. For the purpose of determining the significance of the skin effect in subsea and underground cables, single-core flat formation has been chosen for investigation in this work, where proximity effect is insignificant.

Voltage Drops in the Cable System

An equivalent circuit for the impedance of a single-core coaxial cable consisting of a core, insulation and sheath is as shown in Fig. 4. Currents flowing into the core, insulation, sheath and armour are through I_c, and I_s,

The voltage drop equation for the single-phase cable is given as:

$$\begin{bmatrix} \Delta V_c \\ \Delta V_s \end{bmatrix} = \begin{bmatrix} R_c + jX_c & -jX_m \\ -jX_m & R_s + jX_m \end{bmatrix} \begin{bmatrix} I_c \\ I_s \end{bmatrix} \tag{1.4}$$

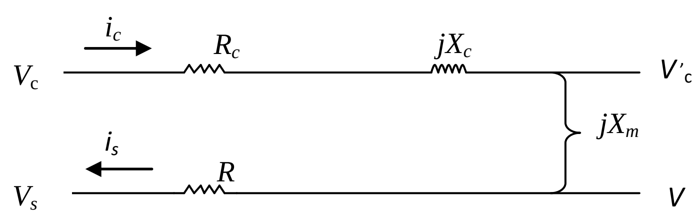


Figure 4. An equivalent circuit for impedances of a single-core underground cable

Since there is no insulation between the metallic screen and the core conductor, it is therefore assumed that the two layers are short-circuited as seen in equation (1.4) [14].[15]

When the cable sheath is solidly bonded to the ground as shown in Fig. 5 give rise to equation (1.6)

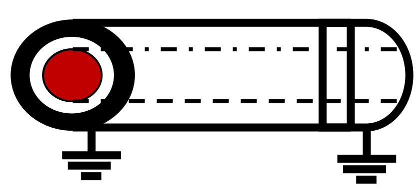


Figure 5. A cable sheath solidly bonded to the ground

$$\begin{bmatrix} \Delta V_C \\ 0 \end{bmatrix} = \begin{bmatrix} R_c + jX_c & -jX_m \\ -jX_m & R_s + jX_m \end{bmatrix} \begin{bmatrix} I_c \\ I_s \end{bmatrix} \tag{1.5}$$

where $$\Delta V_c = \left\{ \left(R_c + R_s \cdot \frac{X_m^2}{R_s^2 + X_m^2} \right) + j \left(X_c - X_m \cdot \frac{X_m^2}{R_s^2 + X_m^2} \right) \right\} I_c \tag{1.6}$$

The Impact of Skin Effect in Power Cables System

It is an established fact that skin and proximity effects generate non-uniformed current distribution as frequency increases, due to the magnetic field inside the conductor, the concentration of current at the centre gradually distribute the current towards the circumference of the conductor, thus increasing the resistance and decreasing the internal inductance.

The impedance of the conductor and sheath considering the skin effect are determined by the impedance of the cable conductor using complex depth concept (Z_c) which is given by

$$Z_c = R_c + jX_c = \sqrt{R_{DC,c}^2 + Z_{\infty,c}^2} \quad (1.7)$$

where $R_{DC,c}^2$ is the DC resistance and is given as

$$R_{DC,c} = \frac{1}{\pi r_c^2 \sigma_c} \quad (1.8)$$

r_c is the radius (m) of the conductor

$Z_{\infty,c}$ is the impedance infinity of the conductor and is given as

$$Z_{\infty,c} = \frac{1}{2\pi r_c \sigma_c p_c} \quad (1.9)$$

where p_c is the complex penetration and is given as

$$p_c = \frac{1}{\sqrt{j\omega\mu_0\sigma_c}} \quad (1.10)$$

Whereas the impedance of the cable sheath (Z_s)

$$Z_s = R_s + jX_s = \sqrt{R_{DC,s}^2 + Z_{\infty,s}^2} \quad (1.11)$$

where

$R_{DC,s}^2$ is the DC resistance in the cable sheath , given as

$$R_{DC,s} = \frac{1}{\pi\left(r_0^2 - r_i^2\right)\sigma_s} \quad (1.12)$$

$\pi\left(r_0^2 - r_i^2\right)$ is the cross-sectional area (m) of the sheath

r_0 is the outer radius (m) of the sheath

r_i is the inner radius (m) of the sheath

σ is the earth conductivity in S/m

the $Z_{\infty,s}$ is the impedance infinity of the sheath , given as

$$Z_{\infty,s} = \frac{1}{2\pi r_0 \sigma_s p_s} \quad (1.13)$$

where p_s is the complex penetration and is given as

$$p_s = \frac{1}{\sqrt{j\omega\mu_0\sigma_s}} \tag{1.14}$$

The skin effect is determined by

$$Z_{skin} = \sqrt{R_{DC}^{\ 2} + Z_{\infty}^{\ 2}} \tag{1.15}$$

The mutual reactance between the conductor and sheath is determined by

$$X_m = \frac{\omega\mu_0}{2\pi}.\ln\frac{r_0}{\frac{r_0 + r_i}{2}} \tag{1.16}$$

Due to the shielding effect of the conductor and sheath there is mutual magnetic coupling between the outer most loop. The coupling is entirely through the earth path. In the overhead transmission lines, the mutual reactance between phase conductors is the sum of external mutual reactance due to the magnetic fields in the air paths and those arising from the earth paths [9][14]. In the case of underground cable the mutual reactance are totally contributed by the earth path only.

The self ground impedance of cable i is given as

$$Z_{ll} = \frac{j\omega\mu_0}{2\pi}.\ln\left(1 + \frac{p_e}{r_0}\right) \tag{1.17}$$

The mutual ground impedance between cables i and j in Fig. 4 is given as

$$Z_{lm} = \frac{j\omega\mu_0}{2\pi}.\ln\left(1 + \frac{p_e}{d_{lm}}\right) \tag{1.18}$$

where p_e is the complex penetration and is given as

$$p_e = \frac{1}{\sqrt{j\omega\mu_0\sigma_g}} \tag{1.19}$$

The self ground admittance and the mutual ground admittance are determined by

$$Y_{sh} = \left(\frac{1}{R_i} + j\omega.2\pi\varepsilon_0\varepsilon_r\right).\left\{\ln\frac{r_i}{r_c}\right\}^{-1} \tag{1.20}$$

where R_i is the insulation resistance

ε_r is the insulation relative permittivity

3. TEST CASE

A 400kV, three-phase underground cable system made up of three single-phase cables lying in the earth bed at a depth of 2m in a flat configuration and the conductor temperature is 90 °C under operation, as shown in Fig. 6, is used to assess its harmonic response to a voltage and current excitation. For safety reasons, solid-bonding of the sheath and armour have been adopted.

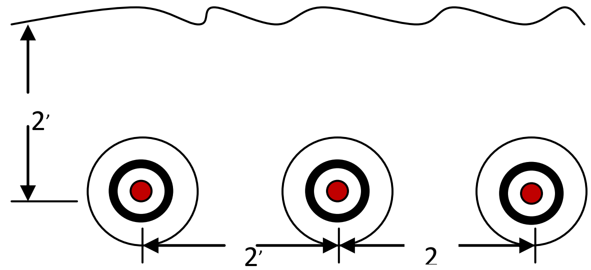


Figure 6. Geometry of the case study three single-phase cables laying in a flat configuration

The characteristics of the cable are: 250-kcmil, concentric strand, paper insulated with solidly bonded, grounded lead sheath.

4. SIMULATION RESULTS

The equivalent impedance is given a

Z =

1.0262 + 1.0069i	0	0
0	1.0262 + 1.0069i	0
0	0	1.0262 + 1.0069i

The ground return is given as

Z_{ground} =

1.0e+002 *

0.1973 + 1.8510i	0.1932 + 0.9393i	0.1891 + 0.7694i
0.1932 + 0.9393i	0.1973 + 1.8510i	0.1932 + 0.9393i
0.1891 + 0.7694i	0.1932 + 0.9393i	0

Total impedance of the cable is given as

$Z_{shortcable}$ =

1.0e+002 *

0.2075 + 1.8611i	0.1932 + 0.9393i	0.1891 + 0.7694i
0.1932 + 0.9393i	0.2075 + 1.8611i	0.1932 + 0.9393i
0.1891 + 0.7694i	0.1932 + 0.9393i	0.2075 + 1.8611i

Admittance of the cable

$Y_{shortline}$ =

1.0e-004 *

0 + 0.9345i	0	0
0	0 + 0.9345i	0
0	0	0 + 0.9345i

The distributed parameter ABCD of the cable are given as

A =

0.1405 - 0.2768i	1.0469 - 0.2698i	0.9238 - 0.2233i
1.0469 - 0.2698i	0.2084 - 0.2443i	1.0469 - 0.2698i
0.9238 - 0.2233i	1.0469 - 0.2698i	0.1405 - 0.2768i

B =

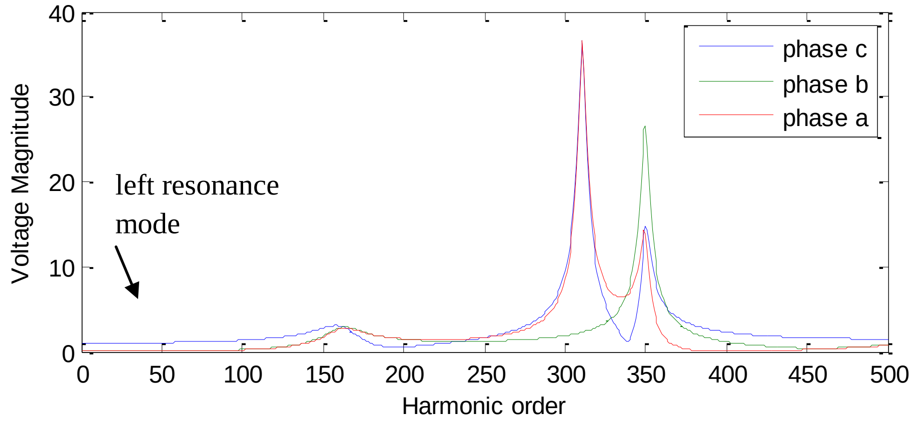
57.3321 - 45.8104i	64.8186 - 40.9288i	61.2272 -11.9246i
64.8186 - 40.9288i	66.3347 - 21.9019i	64.8186 - 40.9288i
61.2272 - 11.9246i	64.8186 - 40.9288i	57.3321 - 45.8104i

C =

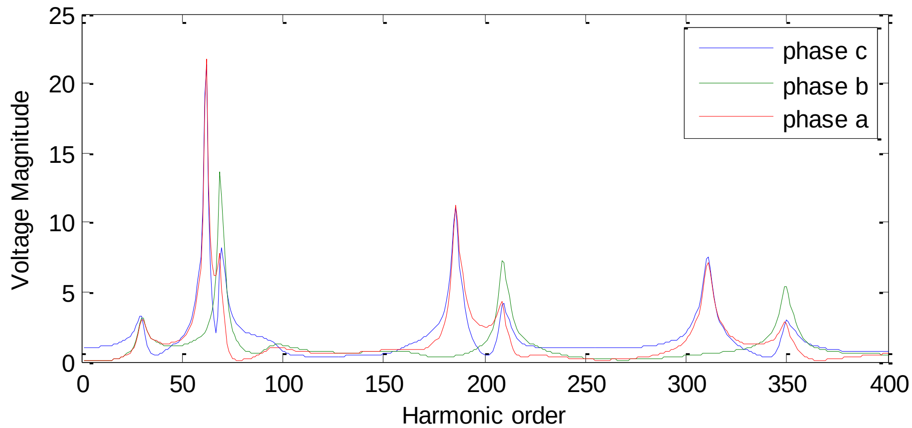
0.0057 - 0.0065i	0.0074 - 0.0054i	0.0068 + 0.0051i
0.0074 - 0.0054i	0.0066 + 0.0033i	0.0074 - 0.0054i
0.0068 + 0.0051i	0.0074 - 0.0054i	0.0057 - 0.0065i

D =

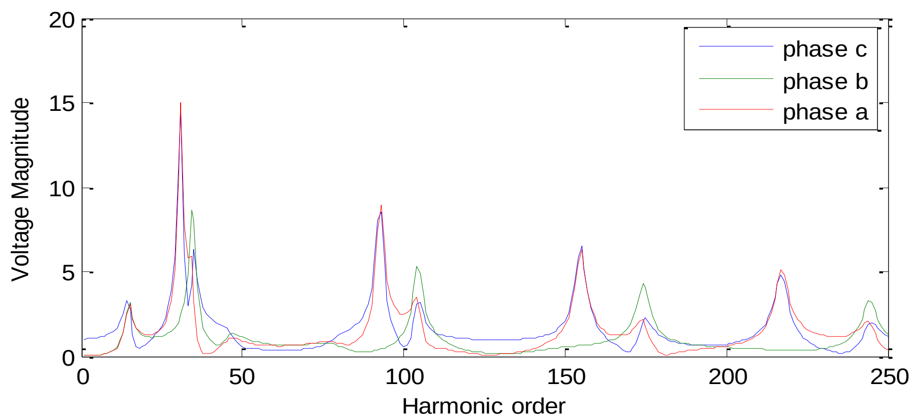
0.1405 - 0.2768i	1.0469 - 0.2698i	0.9238 - 0.2233i
1.0469 - 0.2698i	0.2084 - 0.2443i	1.0469 - 0.2698i
0.9238 - 0.2233i	1.0469 - 0.2698i	0.1405 - 0.2768i



(a)



(b)



(c)

Figure 7. Harmonic Impedance without voltage and current excitation

Figure 7 establishes the relationship between the left and right resonance mode. As seen, the effect of including voltage or current excitation at high frequencies is desirable to avoid the left resonance mode, which introduced high standing wave distortion as the transmission line increases. The left resonance mode increases in peak with increase in the line length, while the right resonance mode decreases with lower peaks.

Z_{series} =

57.3321 - 45.8104i 64.8186 - 40.9288i 61.2272 -11.9246i
64.8186 - 40.9288i 66.3347 - 21.9019i 64.8186 - 40.9288i
61.2272 - 11.9246i 64.8186 - 40.9288i 57.3321 - 45.8104i

Y_{shunt} =

0.0163 - 0.0198i -0.0047 - 0.0614i 0.0012 + 0.0837i
-0.0047 - 0.0614i 0.0233 + 0.1145i -0.0047 - 0.0614i
0.0012 + 0.0837i -0.0047 - 0.0614i 0.0163 - 0.0198i

The skin effect is represented as

Z_{skin} = 1.5925 + 1.1804i 1.5925 + 1.1804i 1.5925 + 1.1804i

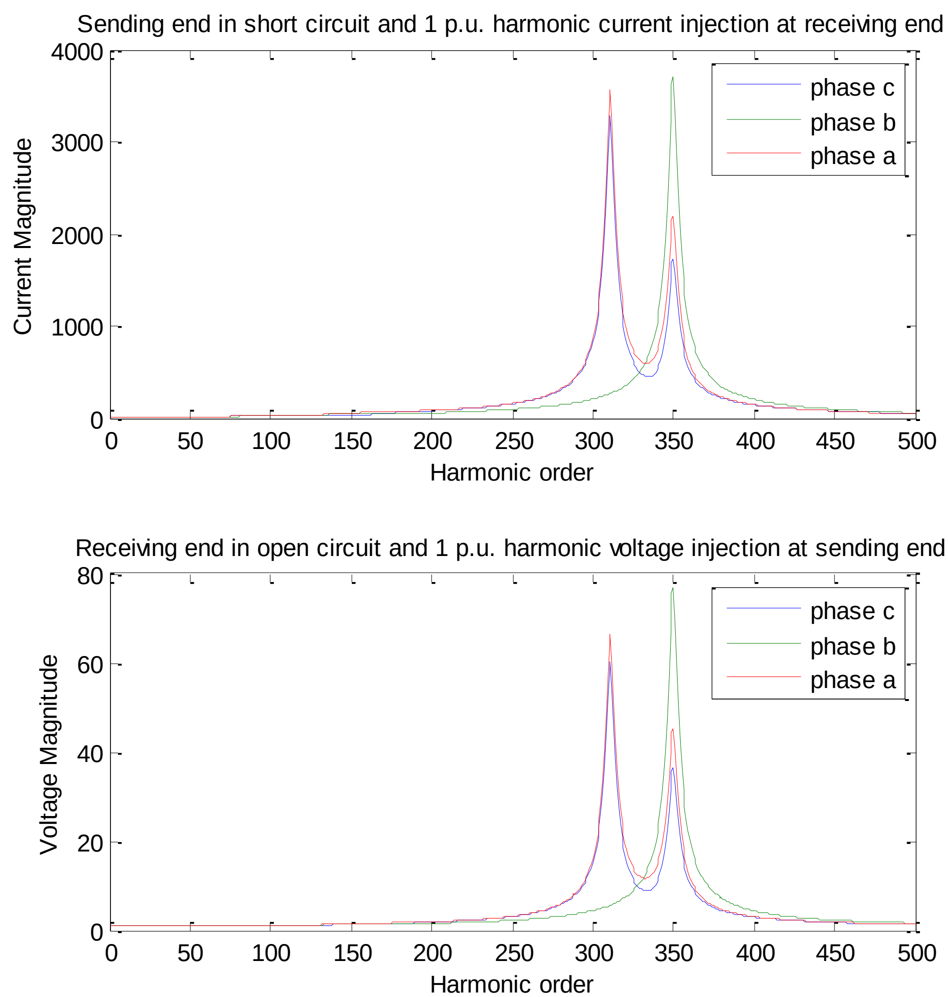
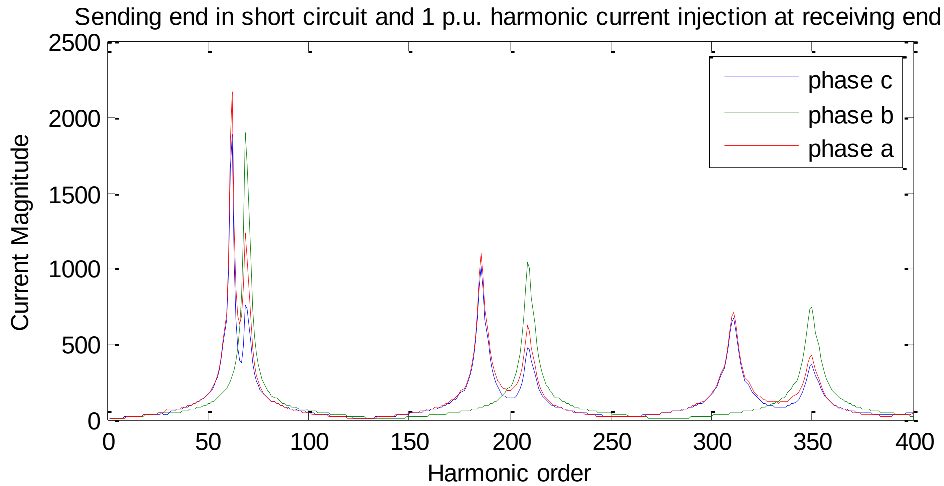


Figure 8. 1km long cable with first resonant peak appear at h = 350, NH = 500



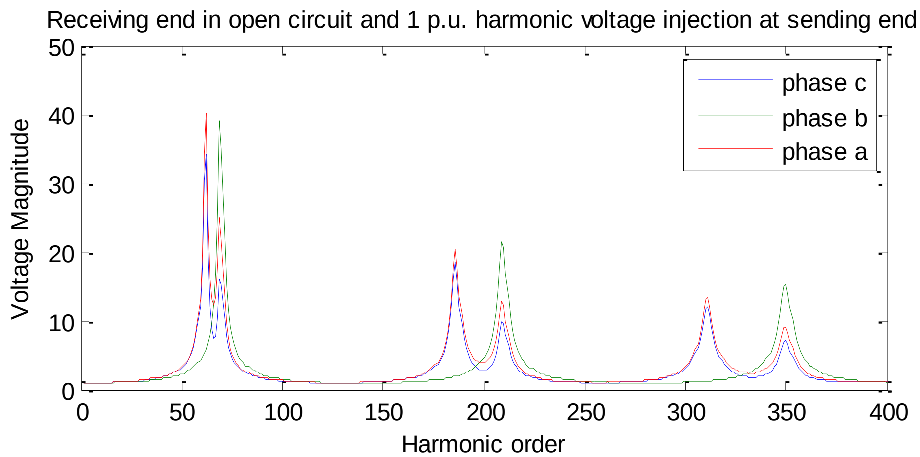
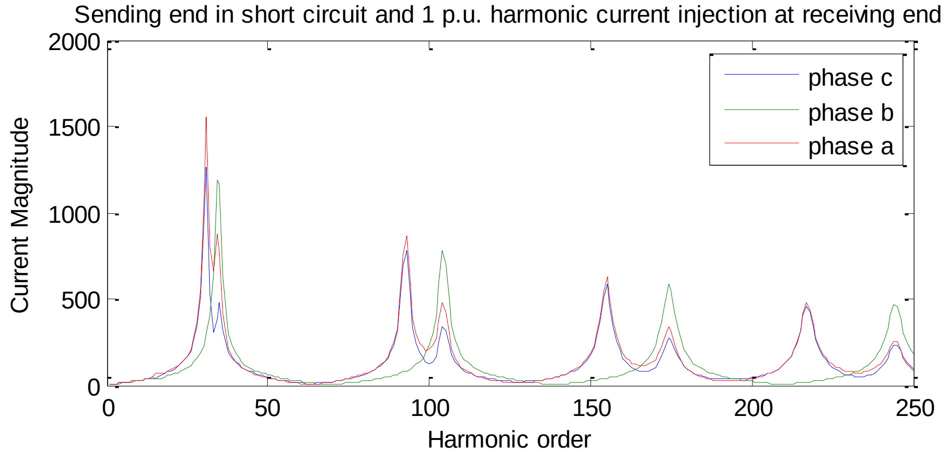


Figure 9 5km long cable with first resonant peak to appear at h = 70, NH = 400, freq. = 50 Hz.



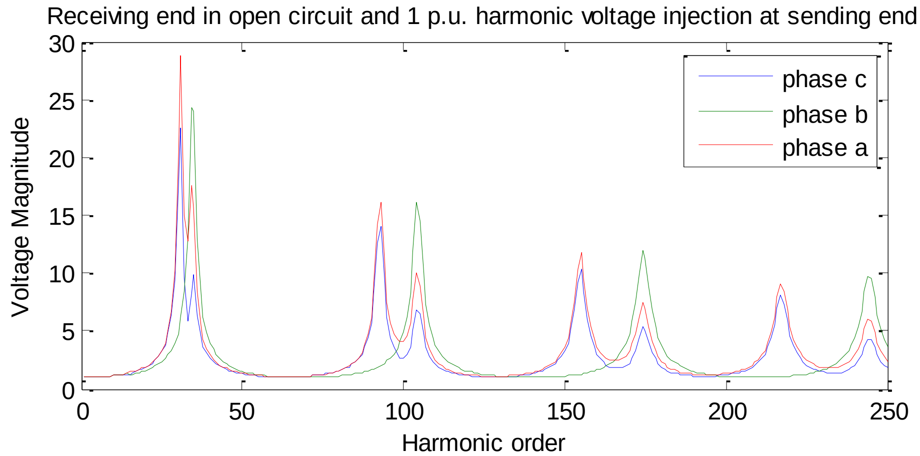


Figure 10. 10km long cable with first resonant peak to appear at h = 30, NH = 250 freq. = 50 Hz.

The above simulations results highlight that two elements are required to create a resonant condition. These are, (1) an excitation source of harmonic current, and (2) an excitation source of harmonic voltage. With full or even partial resonance, voltage distortion can multiply many times the normal system impedance generating harmonic voltage. For resonance to occur, the system must have a substantial percentage of capacitance. In general, parallel resonance in a system is present at a frequency where impedance has very high value. From the above simulation results Fig. 8 to Fig. 10, it can be seen that there are several frequencies where resonance occurs in the system: Fig. 8 manifest only one resonance at with 3rd harmonic voltage. While Fig. 9 exhibit 5th harmonic voltage injection with 40% peak voltage. Also, Fig. 10 shows 5th and 7th harmonic voltage excitation with 28% peak voltage.

5. CONCLUSION

In this paper, developed model of the high voltage underground cable for analysis in frequency domain has been presented. The approximation cable model method has been used to determine the resonant frequencies in the case of a offshore power generation plant connection to the transmission line through high voltage cable. The results indicate that the presence of cables in the power transmission system could contribute to the occurrence of high harmonic resonances at low order harmonic resonant frequencies.

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This study has not received any external funding.

Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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